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ROCK SURFACE ROUGHNESS AS AN INDICATOR OF DEGREE OF ROCK SURFACE WEATHERING

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ABSTRACT

Rock surface weathering often leads to increased rock surface roughness, but roughness has proved difficult to quantify. Several instruments are available for micro-mapping and recording rock surface profiles, but the most appropriate for most purposes is the simple profile gauge. Short profiles can be recorded quickly and accurately. A range of roughness indices has been proposed in other areas of geomorphology and their efficacy as measures of roughness at scales of interest in studies of weathering is assessed. Some are too complex or labour-intensive and others are too sensitive to the scale of roughness to provide reliable measures of magnitude. The most appropriate indicator of both the scale and magnitude of roughness is the standard deviation of the differences between height values at a range of set horizontal intervals along a profile (the 'deviogram'). Varying the measurement interval records roughness at different scales. A regression approach (root-mean-square roughness) provides a reliable measure of the magnitude of roughness at the maximum scale present. Three case studies confirm the efficacy of these approaches to studies of weathering of different rocks in different environments. Software is supplied which automates the calculation of roughness indices from gauge profiles.

KEY WORDS weathering; roughness indices; profile gauge

INTRODUCTION

The weathering of rock surfaces, by chemical, physical and biological processes, often leads to an increase in rock surface roughness. This can take the form of surface pitting, differential relief of crystals, fossils, grains or veins, and in an extreme case 'honeycomb' or alveolar weathering. Rock surface roughness has been used as an indicator of degree of rock surface weathering, particularly in relative-age dating studies, but degree of roughness has usually been estimated subjectively rather than quantified (Blackwelder, 1931; Birman, 1964; Sharp, 1969, 1972; Dugdale, 1972; Boyer and Pheasant, 1974; Nelson, 1980; Birkeland, 1982). If rock surface roughness could be quantified, it might provide a useful surrogate measure of degree of weathering for use in studies of the processes or rates of weathering in different environments and a measure of degree of rock surface weathering for use in relative-age dating of bedrock and boulder surfaces.

Roughness, however, is an enigmatic property. Defined as an antonym of smooth, differences in surface roughness are often obvious yet they have proved difficult to quantify satisfactorily. Evans (1981, p.34) describes roughness as 'a vague and complex concept, for which there is no single satisfactory scale'. The problem lies in the scale-dependence of roughness. A surface can be defined as smooth but uneven or non-planar at one scale or for one purpose, but if the same surface is viewed at a larger scale or for another purpose the unevenness may be interpreted as roughness. To a racing car aiming to set a land-speed record the cracked surface of a playa lake represents an exceedingly smooth natural surface; but it is far too rough

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for a game of marbles. In this sense roughness is not an objective property of natural surfaces but a mental construct, predefined according to the scale of irregularity that is of interest.

A plethora of 'roughness indices' has been used in geomorphology, applied at scales ranging from a few millimetres to entire landscapes. For example, McCarroll (1991, 1992) attempted to quantify rock surface roughness at the point of impact of a Schmidt hammer (4 mm transects) and compared the roughness of boulder surfaces (4·5 cm transects) with their mode of transport. At a larger scale (12·8 m profiles), Sharp *et al.* (1989) followed Nye (1970) in attempting to quantify rock surface roughness as a variable influencing glacier dynamics. Perhaps the most common use of roughness indices in geomorphology has been in describing hillslope profiles (Stone and Dugundji, 1965; Blong, 1975; Parsons, 1978; Klein, 1981; Crowther and Pitty, 1983), and similar techniques have been extended to three dimensions to quantify the roughness of different landscapes (Smith, 1950; Hobson, 1972) and even the roughness of lunar and planetary surfaces (Schloss, 1966; Ronca and Green, 1970). Three-dimensional roughness is of particular interest in the field of remote sensing and there is a substantial literature on the effect of rough surfaces on the scattering of electromagnetic radiation (Ulaby *et al.*, 1982; Lillesand and Kiefer, 1994). There is also a substantial literature on quantifying the roughness of soil surfaces (see reviews in Bertuzzi *et al.* (1990) and Huang and Bradford (1992)) and in the fields of rock mechanics, metallurgy and tribology (e.g. Thomas, 1978; Brown and Scholz, 1985; Power and Tullis, 1991; Hutchings, 1992).

In this paper we propose a standard procedure for recording and quantifying the roughness of rock surfaces at scales that may reflect differences in rock surface weathering. The techniques are illustrated using artificial and real rock surface profiles. The efficacy of the proposed approach is demonstrated using case studies involving different lithologies and weathering environments.

RECORDING ROUGHNESS

The most common approach to quantifying roughness, irrespective of the scale of investigation, is to record relative heights at set intervals. In the general geomorphometric approach to landscapes, the roughness of an area is quantified using altitude measurements on a grid (Evans, 1972). In hillslope studies, slope profiles are normally recorded using segments of equal length (Parsons, 1988).

At the smaller scale of bedrock surfaces, Swantesson (1989) describes a device for precise micro-mapping of rock surfaces. It comprises a motorized laser gauge probe mounted on a frame and is capable of recording about 120 000 height values, with a resolution of 0·1 mm, within an area about 40 × 40 cm. A similar device permitting line-scans with a length of approximately 1 m is also described, and optical scanning techniques have also been used in mapping soil surfaces (Rice *et al.*, 1988; Romkens *et al.*, 1988; Huang and Bradford, 1990, 1992). Such accurate mapping of rock surfaces could be extremely valuable, for mapping and recording the deterioration of engraved rock art for example. However, the technique is time-consuming (2 h per site), requires heavy and expensive measuring and recording equipment, and analysis of recorded values requires substantial computing power, so the technique is clearly not suitable for most weathering studies. In most studies, spatial variation in degree of weathering renders a large sample more important than extreme accuracy.

A much simpler, manual device for measuring rock surface profiles has been described by McCarroll (1992). The 'micro-roughness meter' comprises an engineer's dial (or digital) gauge which slides along a graduated bar mounted on an adjustable tripod. The vertical resolution is 0·01 mm and the length of transect is up to 20 cm. It has been used to measure the width and differential relief of adjacent mineral grains as well as relative heights at set horizontal intervals on transects. Whalley (1994) has recently described a similar but automated version. Larger scale profiling instruments have been used to record soil surfaces (e.g. Keupers, 1957; Shakesby, 1993) and could equally be used to record larger scale rock surface profiles.

The simplest and most convenient instrument for recording rock surface profiles at scales likely to be of interest in weathering studies is the profile gauge. These are used by carpet-fitters to record the profile of obstructions and a wide variety is available. The most suitable version that we have found, the 'Profile-Master', comprises a 19 cm line of 209 freely moving pins arranged in groups of 11 (Figure 1). The instrument is pressed against a rock surface and the profile transferred to millimetre graph paper in the field. A large sample of rock surface profiles can be collected quickly and easily.

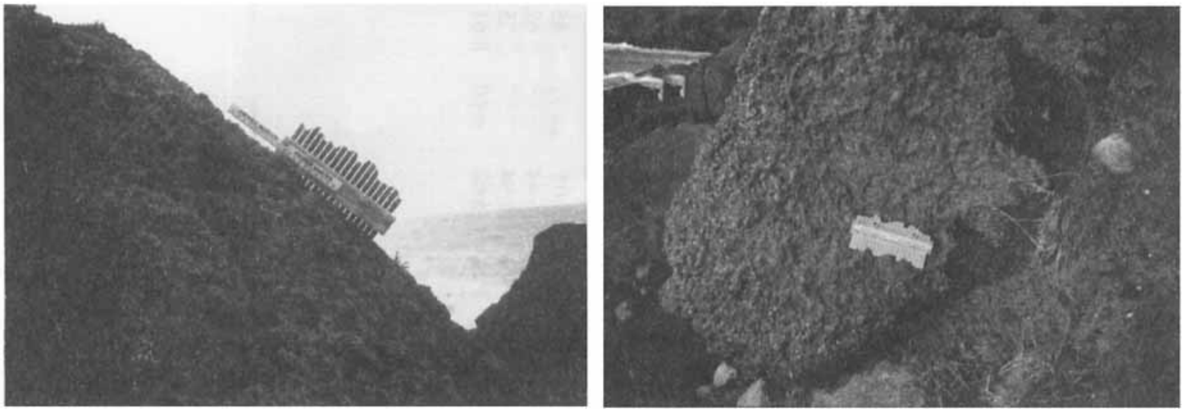

Figure 1. The 'Profile-Master' profile gauge on (A) honeycomb-weathered hornblende picrite at Porth Ysgo, North Wales and (B) on a boulder of the same lithology eroding out of the cliff. The instrument comprises a 19 cm line of 209 freely moving pins

QUANTIFYING ROUGHNESS

The total line length of a road or river divided by the straight-line distance between the end points is commonly used as a measure of sinuosity (Nordbeck, 1964; Timber, 1967; Unwin, 1981). The same technique has been used to quantify the roughness of hillslope profiles, based on the ratio of the length of the profile line to that of the straight-line distance between the two end points (Blong, 1975; Klein, 1981). The 'chain' method used in soil science (Saleh, 1993) relies on the same principle. Although this index has the advantage of being simple to calculate, the resulting values do not seem to reflect surface roughness at the scales that are of interest here. Figure 2 displays four artificial profiles drawn to yield identical sinuosity values (Table I), but which clearly differ in terms of surface roughness. It is notable that even at the hillslope scale at which it has been used previously, the results are not consistent with other measures of roughness applied to the same profiles (Blong, 1975).

In calculating terrain roughness from maps, one approach is to use the 'local relief', calculated as the difference between the highest and lowest elevations occurring within a defined area (Mark, 1975). This approach deals with variation from the horizontal, so it is not appropriate for use on hillslopes, but it

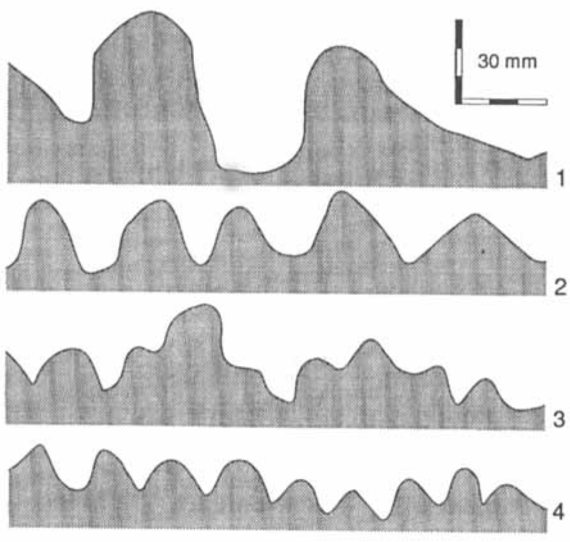

Figure 2. Four artificial 'test profiles' drawn to yield identical sinuosity values but which differ markedly in roughness

Table I. Roughness indices obtained from the four 'test profiles'

Profile	Mean local relief (mm) 5 mm	10 mm	15 mm	20 mm	25 mm	30 mm
1	5·32	10·76	16·00	20·75	25·75	31·03
2	5·61	11·03	15·19	18·39	20·06	21·36
3	4·86	8·78	12·03	14·46	16·18	17·97
4	5·26	9·30	11·40	12·57	13·32	13·91

Profile	Number of changes of curvature 5 mm	10 mm	15 mm	20 mm	25 mm	30 mm
1	0·31	0·34	0·41	0·58	0·78	0·80
2	0·28	0.50	0·79	0.88	0·70	0·85
3	0·44	0·81	0·55	0·73	0·70	0·85
4	0·47	0·91	0·62	0·50	0·57	0·65

Profile	Roughness index B (mm) 5 mm	10 mm	15 mm	20 mm	25 mm	30 mm
1	4·24	12·93	27·08	40·55	43·93	53·15
2	5·90	15·93	24·69	23·83	21·05	14·54
3	7·13	13·62	12·63	18·60	19·36	21·81
4	7·25	15·22	10·56	6·85	7·41	11·61

Profile	Mean difference in gradient (degrees) 5 mm	10 mm	15 mm	20 mm	25 mm	30 mm
1	19·58	33·65	48·06	53·38	65·57	71·33
2	32·90	57·89	71·28	65·20	42·01	25·63
3	44·73	55·69	39·35	39·08	37·01	35·85
4	52·20	68·62	35·08	17·72	15·82	21·21

Profile	Variance (mm) 5 mm	10 mm	15 mm	20 mm	25 mm	30 mm
1	64·1	220·5	419·2	627·5	824·2	989·1
2	49·6	149·1	223·0	238·4	187·8	112·7
3	43·0	95·5	116·5	142·6	181·0	214·8
4	35·4	73·7	56·8	31·6	43·6	74·2

Profile	Root variance (mm) 5 mm	10 mm	15 mm	20 mm	25 mm	30 mm
1	8·01	14·85	20·47	25·05	28·71	31·45
2	7·04	12·21	14·93	15·44	13·70	10·62
3	6·56	9·77	10·79	11·94	13·45	14·65
4	5·95	8·58	7·54	5·62	6·60	8·61

Profile	Index A 5 mm	10 mm	15 mm	20 mm	25 mm	30 mm	Regression R^2	r.m.s. (mm)
1	7·96	14·76	20·34	24·89	28·54	31·28	0·18	16·32
2	7·04	12·21	14·93	15·44	13·70	10·61	0·00	8·40
3	6·54	9·73	10·75	11·88	13·36	14·49	0·17	8·40
4	5·95	8·57	7·50	5·51	6·53	8·58	0·27	5·31

can be applied to short profiles obtained from rock surfaces. The profile is recorded using a gauge, transferred to millimetre graph paper and the maximum difference in height in, for example, each 10 mm interval is recorded and the overall mean calculated (Table I). This approach was adopted by Nesje *et al.* (1994), using a 5 mm interval on 19 cm profiles to quantify rock surface roughness on six mountains on a transect across southern Norway.

A problem with this approach is its sensitivity to the overall slope of the profile. A smooth, planar horizontal surface will yield a value of zero but any deviation from the horizontal results in a spurious 'roughness' value. With rough gauge profiles, the angle at which the profile is transferred to the graph paper is critical. The profiles in Figure 2 were transferred by aligning the needles of the profile gauge vertically, so that the profiles appear approximately horizontal. However, this is a rather arbitrary process and the resulting angle of the profile depends upon the angle at which the gauge was presented to the rock surface.

A more serious problem with local relief is that it is difficult to automate its calculation. The values need to be calculated from the original profiles. The interval of measurement must either be defined on *a priori* grounds, or separate measurements and calculations must be made for each range of measurement intervals. Also, Evans (1972) notes that when this approach is applied to landscapes, if the measurement interval is so small that it is unlikely to contain a whole slope, then 'relief' becomes simply a measure of gradient. The measurement of gradient is easily automated (see below), so there is little advantage in applying this approach.

Although mean local relief provides an effective measure of magnitude of roughness when the measurement interval is large, and has the advantage of incorporating the maximum variation within recorded profiles, it is a labour-intensive procedure suitable only for small data sets.

In attempting to quantify the roughness of hillslope profiles, Parsons (1978, p.434) proposed 'the number of changes of curvature measured as the number of times the angular difference between adjacent segments changes from positive (convex) to negative (concave) or *vice versa*'. The same measure, termed 'the number of turning points', where a turning point is defined as a reversal in the direction of change of slope angle, was used by Blong (1975), who also used the ground surface length divided by the number of turning points. A problem with this approach is that it does not take account of the magnitude of the changes of curvature. Although it provides a ratio-scale index, it is based on extracting only nominal-scale data (+ or −) from the measured profiles. Also, the values cited by Parsons (1978) show no correlation with the other roughness index he uses (mean value of angular difference between adjacent hillslope segments), which does take account of differences in magnitude.

The mean absolute difference between adjacent height differences on a profile was proposed by McCarroll (1992) for use with the micro-roughness meter (index B). It can be used to investigate roughness at a variety of scales by varying the measurement interval. A related measure used by Parsons (1978) on hillslopes is 'the mean value (in degrees) of the angular difference between all adjacent segments'. Crowther and Pitty (1983) used a similar measure based on 'the mean square of differences in angle between adjacent measured lengths along profiles'.

These techniques based on changes of curvature and slope are too sensitive to the scale of roughness to provide reliable measures of magnitude, particularly at smaller measurement intervals. In particular, they are sensitive to the length of different slope sections within a profile. For example, profile 1 comprises long regular slopes and therefore yields low index B roughness values when a small measurement interval is used, but very high values when the measurement interval is more than half of the average width of the roughness elements (Table I).

Fourier and spectral analysis techniques view profiles as resulting from overlapping sine curves of varying wavelength and amplitude. They are commonly applied to time-series data and spectral analysis in particular has been used widely in defining periodicities in, for example, proxy indicators of climate. A few attempts have been made to apply these techniques to landscapes (Rayner, 1971, 1972; Pike and Rozema, 1975). Just as the device described by Swantesson(1989) is too accurate and detailed for most purposes, these techniques are too complex and the results too difficult to interpret and compare. Moreover, Evans (1981, p.37) notes that 'each profile in a data set must be long enough to include numerous examples of all the important wavelengths', so they are not appropriate for quantifying rock surface roughness using short profiles such as those recorded using a profile gauge.

Several attempts have been made to use the fractal dimension (D) of a profile as an index of rock surface roughness (Brown and Scholz, 1985; Power and Tullis, 1991; Huang *et al.*, 1992; Odling, 1994; Den Outer *et al.*, 1995). However, there is no evidence to support the assumption that weathered rock surfaces are self-similar over a wide range of scales and even self-similarity over restricted scales of measurement has not been demonstrated convincingly. If the fractal dimension varies with the scale of measurement there is little advantage in using it. It is more logical to use the variogram from which the fractal dimension is often derived.

The variogram

Variograms are used to relate variance (or semivariance) to spatial separation and provide 'a concise and unbiased description of the scale and pattern of spatial variability' (Curran, 1988, p.494). In soil science, other environmental sciences and remote sensing, where data are available from equally spaced points, they are used to estimate the average value of a property within a region or to interpolate the value of a property at a place that has not been visited. The technique can, however, be used to quantify the roughness of a profile at a range of scales.

If we take a profile with height measurements recorded at regular intervals, the variance is defined as the mean squared difference in height of adjacent values:

$$Vr = 1/N - r \; \Sigma\,(x_i - x_{i+r})^2 \qquad (1)$$

where Vr = incremental variance, x_i = incremental height, N = total number of data points, r = lag. Where height measurements are recorded every 5 mm, then 5 mm corresponds to a lag of one. A variogram is a plot of variance against lag distance and it displays the magnitude of roughness (variance) at different scales (lag distances).

The four 'test profiles' presented in Figure 2 provide a convenient test of the veracity of the variogram as an indicator of both the magnitude and scale of roughness. We would consider the magnitude of roughness to vary considerably between these profiles in the order $1 > 2 \geq 3 > 4$. Profile 1 displays roughness at the largest scale, with roughness elements (peaks and troughs) more than 3 cm in width. Profiles 4 and 2 display roughness elements of about 0·5–1 cm and 1·5–2 cm respectively. Profile 3 is more complex, with roughness elements of about 1–1·5 cm superimposed upon a larger-scale roughness with elements of about 5 cm width.

The variance results place the profiles in the correct order for all measurement intervals except the largest, which reverses the ranks of profiles 2 and 3 (Table I, Figure 3). The different scales of roughness are also clearly reflected. For profile 1 the roughness values increase as the measurement interval increases, whereas for profile 2 the values increase until a measurement interval of 2 cm and then decline. Profile 4 yields relatively high values at intervals of 1 and 1·5 cm and again at 3 cm, which is probably a reiteration of roughness at a scale of 1·5 cm. The results from profile 3 are more complex, with similar values at intervals of 1 cm and 1·5 cm and similar but higher values at intervals of 2–3 cm.

Although the results from the test profiles are promising, there is a problem with the use of variance to

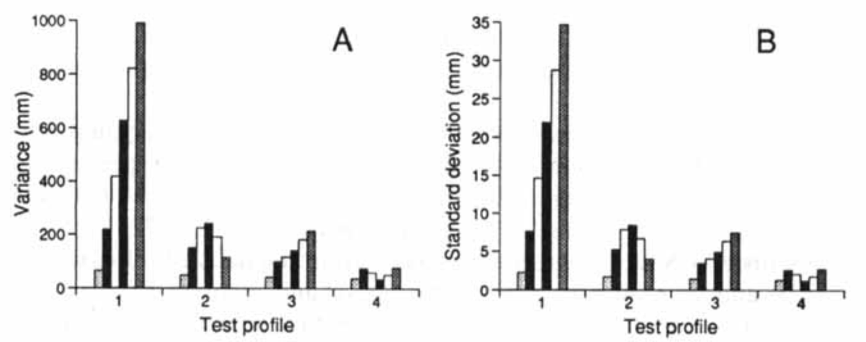

Figure 3. Roughness indices obtained from the four test profiles (Figure 2). Within each histogram the bars represent measurement intervals of, from left to right, 5, 10, 15, 20, 25 and 30 mm. (A) Variogram, (B) 'deviogram'

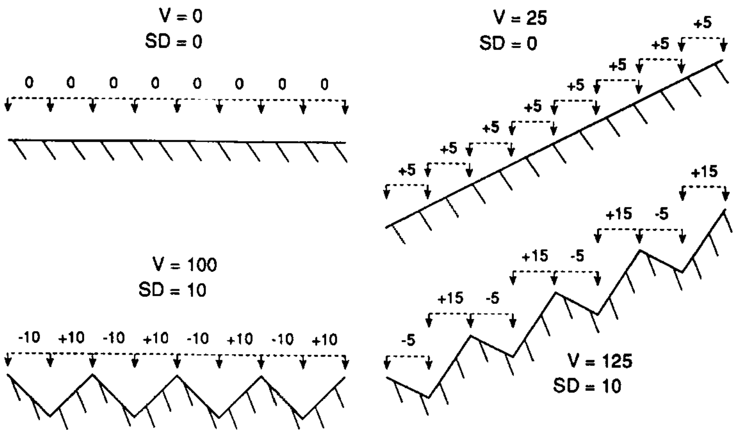

Figure 4. The influence of slope on the variance (V) and the standard deviation (SD) of the differences between adjacent height values. For a perfectly regular, horizontal profile, the standard deviation is equal to the square root of the variance. As the profile is tilted, the variance increases but the standard deviation remains the same

quantify the roughness of real rock surfaces from profiles obtained using a profile gauge or micro-roughness meter. Variance is sensitive to the overall slope of the profile, and as the slope increases so does the variance. Because the calculation of variance does not distinguish positive and negative values (Equation 1), a perfectly smooth planar surface will yield variance values of zero when it is horizontal, but increasing values as the plane is tilted (Figure 4). However, the position in which the micro-roughness meter is placed on the rock surface, or the angle at which the profile is transferred from a gauge to graph paper is arbitrary. Identical surfaces measured or transferred at different angles will yield different roughness values.

One solution to this would be to detrend the profiles, perhaps by calculating the best-fit regression line and adjusting it to the horizontal. However, there is a much simpler method, which is to use deviation from the mean in place of variance.

The 'deviogram'

The standard deviation of the differences between adjacent values was proposed as a measure of rock surface roughness by McCarroll (1992). For a perfectly regular, horizontal profile, where the rising and falling elements of the slope are equal, the mean difference between all adjacent height values will be zero, so the standard deviation of the height differences will be equal to the square root of the variance (Figure 4). For the four test profiles, which are near-horizontal, the standard deviation values for each measurement interval are close to the square root of the variance (Table I). If, however, a profile is artificially 'tilted' by adding numbers in a numerical progression to the original height values, the variance values increase but the standard deviation values remain unchanged (Figure 4). In effect, using the standard deviation rather than the variance automatically detrends the profiles, and the angle at which they are measured or transferred becomes irrelevant. A 'variogram' plotted using standard deviations rather than variance values might be termed a 'deviogram'. The 'deviogram' is here proposed as the optimum way to quantify and display both the magnitude and scale of roughness of rock surface profiles.

Regression, or root-mean-square roughness

It would seem reasonable to suggest that some measure of the deviation of points above and below a best-fit line drawn through a profile might provide a measure of roughness. Using the digitized height values at 5 mm intervals, regression analysis is a simple procedure. It is a common misconception that the Pearson product–moment correlation coefficient (the r-value) provides a measure of such deviation, but it does not. The r-value is related to the deviation from the regression line but also to the slope of the line, so that near-horizontal profiles will yield low values irrespective of roughness. A more appropriate index is the standard error of the y-estimate, which is part of the regression output of most spreadsheets. The same approach was

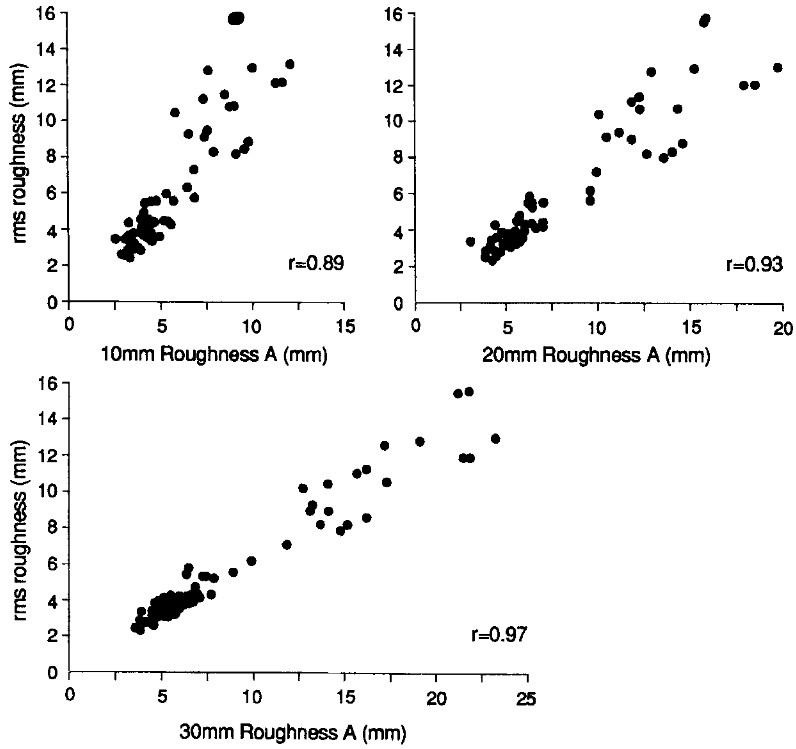

Figure 5. The relationship between roughness indices obtained using the regression approach (r.m.s. roughness) and index A roughness values obtained using different measurement intervals. Data are from the 60 profiles from Porth Ysgo. Pearson's product moment correlation coefficients (r-values) are included

used by Blong (1975) on hillslope profiles. This measure is equivalent to the root-mean-square (r.m.s.) roughness commonly used to define the surface texture of metal surfaces in tribology, which is defined as the root-mean-square deviation of the profile from the mean line (Hutchings, 1992). The mean line is defined so that equal areas lie above and below it and it is usually calculated automatically by the profiling instrument.

The regression approach has the advantage that it is a simple automated procedure, but is sensitive to the overall shape of a profile as well as its roughness. A smooth planar surface will yield a zero value irrespective of any deviation from the horizontal, but a smooth curved or undulating surface will yield a spurious roughness value. Where the regression approach is used, care should be taken to record only planar as opposed to clearly curved surfaces. The recording or exclusion of 'undulating' surfaces depends on the scale of roughness that is of interest.

The regression approach was used to calculate the roughness of the four 'test profiles'. As expected, the Pearson product–moment correlation coefficient yields low values because the profiles are near-horizontal (Table I). However, the standard error of the y-estimate (r.m.s. roughness) places the four test profiles in the preferred order, with profiles 2 and 3 yielding the same value.

The relationship between the regression approach to roughness and the various scales of roughness reflected by the 'deviograms' (index A) is displayed in Figure 5. The r.m.s. roughness values are highly correlated with standard deviation values and the correlation improves as the measurement interval increases. At small measurement intervals, a large range of r.m.s. values is obtained from profiles which yield similar standard deviation (index A) values. Consulting the original profiles suggest that this reflects the underestimation by index A of the roughness of profiles where both the scale and magnitude of roughness are high. At larger measurement intervals there is a very good correlation between the results of the regression approach and index A, suggesting that the former provides a useful measure of roughness at the maximum scale present on the profile.

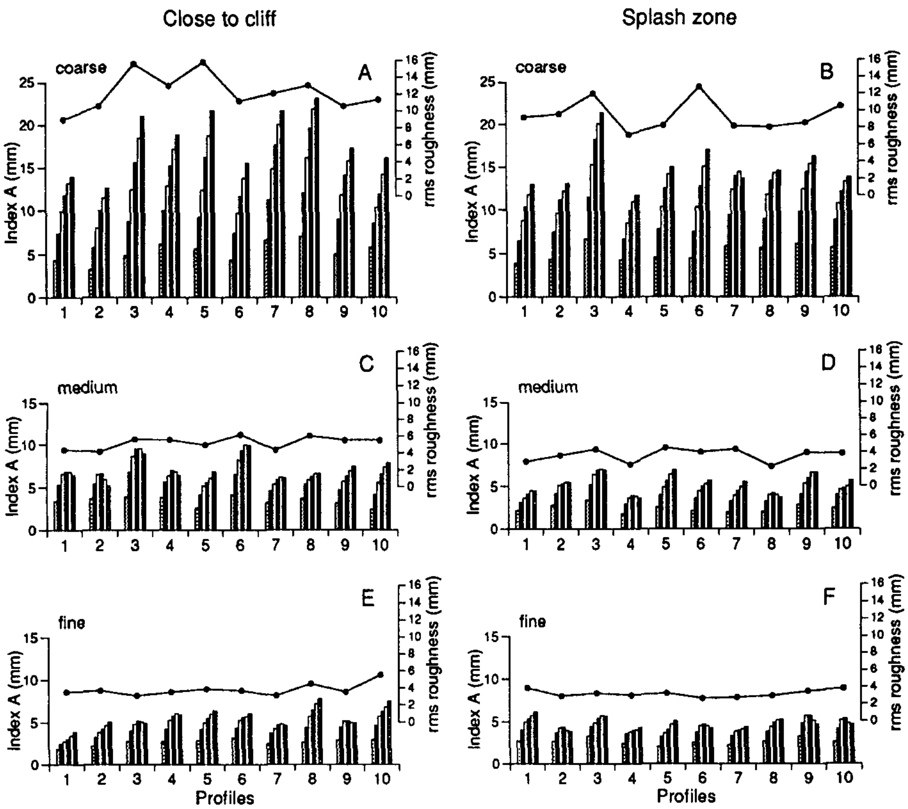

Figure 6. Roughness indices obtained using index A and the regression approach (r.m.s. roughness) from six large boulders of hornblende picrite at Port Ysgo, north Wales. Boulders A and B display large-scale roughness, with mineral concentrations 3–4 cm in width (coarse). Boulders C and D have mineral concentrations of *c.* 2 cm (medium) and boulders E and F of *c.* 1 cm (fine). Boulders A, C and E lie close to the cliff, boulders B, D and F lie in the splash zone above high tide. Within each histogram (deviogram) the bars represent measurement intervals of, from left to right, 5, 10, 15, 20, 25 and 30 mm

The suitability of the 'deviogram' and the regression approach for quantifying the magnitude and scale of roughness of real rock surfaces was tested at a coastal site (Porth Ysgo, discussed later in a case study) where large boulders of the ultrabasic rock hornblende picrite are weathering *in situ* within glacial deposits and are being released by coastal erosion. In this unusual rock, which forms part of a layered igneous complex (Gibbons and McCarroll, 1993), preferential diffusion of ions towards intercumulus nuclei has resulted in segregated pools of intercumulus minerals. Differential chemical weathering results in marked surface roughness, with plagioclase-rich concentrations producing protuberances and hornblende or clinopyroxene concentrations the hollows (Hawkins, 1965, 1970). However, both the scale and magnitude of roughness vary in response to the size of the mineral concentrations. Close to the cliff, 10 profiles were measured on each of three large boulders with mineral concentrations of about 3–4 cm, 2 cm, and 1 cm. The same sampling scheme was applied on three boulders in the splash zone above high-tide level, yielding a sample of 60 profiles (Figure 6).

The different scales as well as magnitude of roughness are clearly reflected in the 'deviograms' (Figure 6). On the coarsest boulders (A and B) the roughness values increase as the measurement interval is increased. On the boulders with medium and small mineral concentrations (C to F) the results are more complex. Smaller measurement intervals yield relatively high roughness values which are then reiterated by the larger intervals. Each profile was examined and the 'deviograms' are considered to present a realistic reflection of both the scale and magnitude of roughness of these real rock surface profiles.

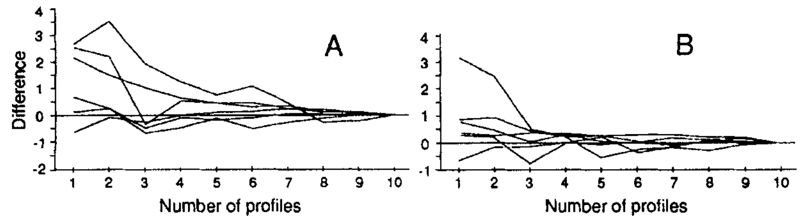

Figure 7. Test of the number of profiles required from each boulder. Cumulative mean roughness indices ((A) index A 20 mm; (B) r.m.s. roughness) are compared with the mean value after 10 profiles. Data are from Porth Ysgo

PROPOSED STANDARD PROCEDURE

Recording surface profiles using a profile gauge is a relatively simple procedure. One end of the instrument is pressed against the surface and the other end is then placed on graph paper and traced, care being taken to mark the top surface. In this way a large sample of profiles can be collected quickly. Where a study involves quantifying the roughness of boulder as opposed to bedrock surfaces it is useful to know how many profiles are required from each boulder to provide representative mean roughness values. This can be tested using the 10 profiles measured on each of the six boulders of varying texture at Porth Ysgo. It is clear from Figure 7 that the mean values obtained using the regression approach, and index A using a 2 cm interval, stabilize after only four profiles. Similar results were obtained for the other measurement intervals. This suggests that even on the very rough boulders included here, four profiles per boulder are sufficient and extra effort is best spent on increasing the number of boulders per site.

Having recorded the profiles, roughness can be calculated by hand, but it is much simpler to extract information from the profiles in the form of digital data. This can be done very simply using a digitizing tablet yielding x and y coordinates. For most purposes it is sufficient to record relative heights at 5 mm intervals. Where it is necessary to investigate roughness at a smaller scale it is preferable to use the much more accurate micro-roughness meters (McCarroll, 1990, 1991, 1992; Whalley, 1994). The digitized data (in millimetres) can be imported into the spreadsheet template provided, which calculates automatically the standard deviation of the differences between adjacent height values (roughness index A) at measurement intervals of 5 mm, 1 cm, 1·5 cm, 2 cm, 2·5 cm and 3 cm. The results are tabulated and presented as a 'deviogram'. The regression approach can also be carried out using the digital data either within the spreadsheet or using a statistics package.

The scale of roughness most appropriate to any particular study can be determined on *a priori* grounds or by considering the array of values obtained using the six measurement intervals. If there is some doubt about the appropriate scale of roughness then it is best to avoid the smaller measurement intervals, since these will yield anomalously low values on surfaces with large-scale roughness. Where it is necessary to use a single measure to compare surfaces which differ in scale as well as magnitude of roughness, a reasonable compromise is to use a 2 cm measurement interval. It is not advisable to use a smaller measurement interval unless there is some *a priori* reason for focusing only on very small-scale irregularities. Small measurement intervals will result in underestimation of the roughness of many natural rock surfaces. Where the scale of roughness is large, or very variable, and it is not necessary to filter out surface irregularity beyond the scale of what is considered on *a priori* grounds to represent 'roughness', the regression approach can be used.

The regression approach (root-mean-square roughness) provides a convenient and reliable measure of surface roughness at the maximum scale present on a profile. It is particularly useful where the scale of roughness is large, but will yield spuriously high values where surfaces are smooth but not planar.

CASE STUDIES

Three case studies are presented to demonstrate how quantification of rock surface roughness can serve as a surrogate measure of degree of rock surface weathering.

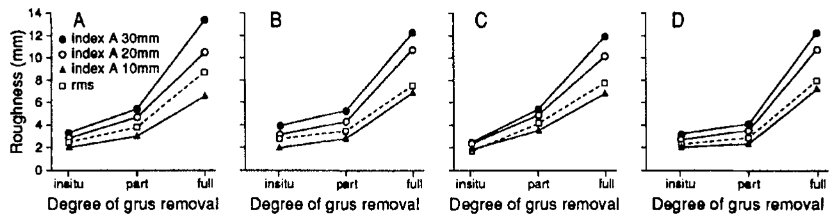

Figure 8. Increase of surface roughness of hornblende picrite due to removal of weathered products (grus). Differential weathering takes place whilst the boulders remain *in situ* within glacial deposits

Weathering and erosion of ultrabasic rock

At Porth Ysgo, on the south coast of the Lleyn Peninsula of north Wales, large boulders of hornblende picrite within glacial deposits are being slowly eroded out of the cliff and litter the shore (Gibbons and McCarroll, 1993). Differential weathering of concentrations of feldspars and of ferromagnesian minerals leads to marked surface roughness. Differential weathering takes place within the glacial deposits but the weathering products (grus) remain *in situ* and when boulders are freshly exhumed from the cliff they display relatively smooth surfaces. However, boulders which protrude from the cliff display a gradation from smooth surfaces close to the till surface to extremely rough diferentially weathered surfaces. This transition from smooth *in situ* surfaces through surfaces with the grus partly removed to fully exposed surfaces can be demonstrated by quantifying the roughness of surfaces within three zones on boulders protruding from the cliff (Figure 8). The results demonstrate clearly the increasing roughness as a result of differential weathering.

The boulders lying immediately below the cliff are extremely rough whereas those further out to sea become increasingly smoothed by marine erosion. This was demonstrated by recording profiles (four per boulder) on 10 boulders in each of five zones: within the cliff, below the cliff, within the salt-spray zone, at high-tide level and below high-tide level. The results clearly display the expected decline in surface roughness (Figure 9). The roughness values increase as the measurement interval increases, suggesting large-scale roughness.

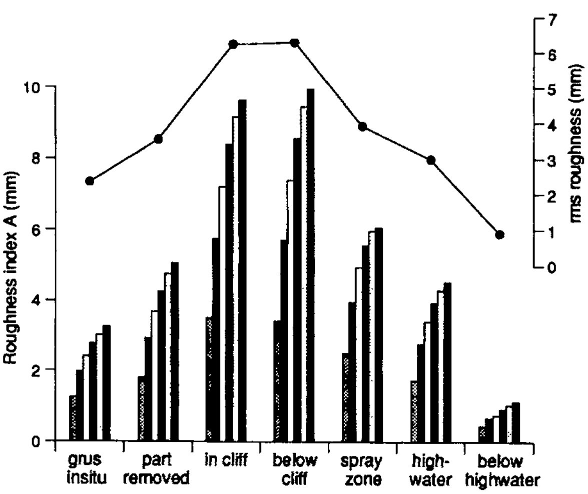

Figure 9. At Porth Ysgo, boulder surface roughness increases as grus is removed, then declines as boulders are smoothed by marine erosion. Each histogram (deviogram) represents the mean values obtained from 40 profiles. Within each histogram the bars represent measurement intervals of, from left to right, 5, 10, 15, 20, 25 and 30 mm

Coastal weathering of limestone

On limestone sea cliffs the dominant weathering processes are likely to vary with height above sea level. Close to sea level, abrasion during storms may result in some erosion. With increasing height, different lichens colonize the surface and salt weathering and chemical weathering combine. The result seems to be a general increase in the roughness of limestone with increasing distance above the sea. This was tested on a small cliff near Rotherslade Bay, west of Swansea on the Gower Peninsula of South Wales. The limestone beds are steeply dipping here so that difference in weathering of a single uniform bed could be investigated. Horizontal profiles were recorded at five heights above the beach. The results confirm the observation that roughness increases (Figure 10) at least to a height of 4 m above the beach.

Rock surface weathering and relative-age dating

Degree of rock surface weathering is commonly used as a relative-age dating technique, particularly for dating glacial deposits dominated by boulders. To test the value of surface roughness as a measure of degree of weathering under such circumstances, 90 surface profiles were recorded from sites of known age in the Oldedalen area of western Norway. All of the sites were on augen gneiss, differential weathering of which leads to increasing surface roughness. The roughness values from Little Ice Age bedrock surfaces (< 250 years since deglaciation) are significantly lower than those obtained from sites in the same valley deglaciated about 9000 years ago (Figure 11). Sites located on the nearby mountain Skåla, which reaches 1843 m, revealed a statistically significant increase in surface roughness above a trimline at 1350 m. This evidence was used by McCarroll and Nesje (1993) to argue that the trimline represents the vertical limit of the last ice sheet in the area, and this is supported by the preliminary results of cosmogenic isotope dating. A similar approach might be used elsewhere for relative-age dating of bedrock and boulder surfaces.

SUMMARY AND CONCLUSIONS

Several instruments are available for recording rock surface profiles or for micro-mapping of rock surfaces. For most weathering studies the spatial variability of surface roughness renders a large sample more important than extreme accuracy, so the simplest instrument may be the most appropriate. Profile gauges, which are inexpensive and widely available, allow short profiles to be recorded quickly and accurately. The profiles are transferred to graph paper in the field.

A wide range of roughness indices has been used in geomorphology, but most are inappropriate for measuring the roughness of rock surfaces at scales of interest for studies of weathering. Fourier and spectral analyses and fractal approaches are too complex and require relatively long profiles. Mean local relief must

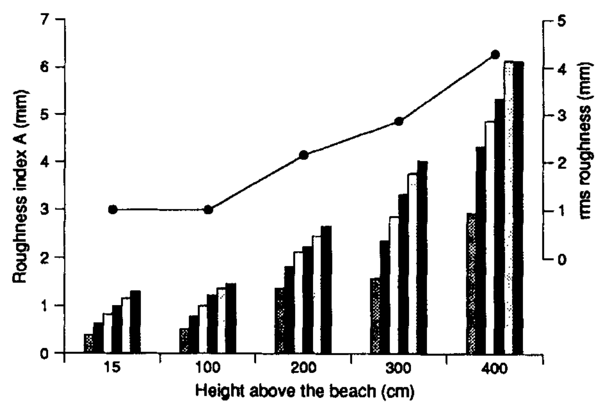

Figure 10. Increase in surface roughness, with height above the beach, of a steeply dipping uniform bed of limestone at Rotherslade Bay, Gower, South Wales. Within each histogram (deviogram) the bars represent measurement intervals of, from left to right, 5, 10, 15, 20, 25 and 30 mm

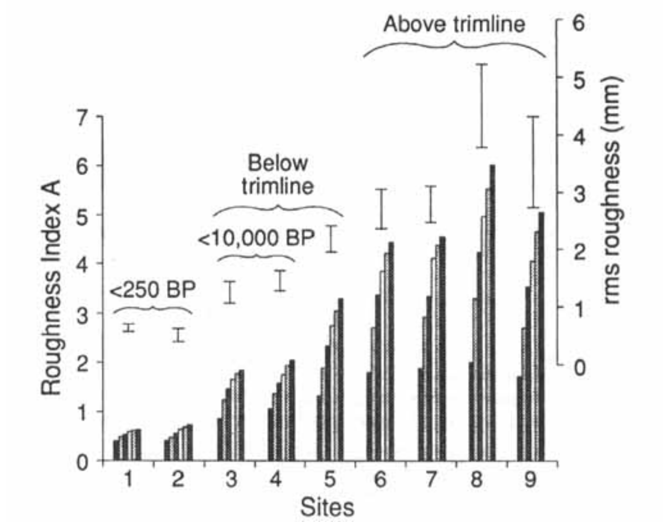

Figure 11. Roughness indices obtained from outcrops of augen gneiss in the Oldedalen area of western Norway. Within each histogram (deviogram) the bars represent measurement intervals of, from left to right, 5, 10, 15, 20, 25 and 30 mm. Each value represents the mean of 10 profiles

be calculated by hand, or from fully digitized profiles, and so is labour-intensive and only suitable for relatively small data sets. Techniques based on changes of slope and curvature are too sensitive to the scale of roughness to provide reliable measures of magnitude.

The most useful techniques are those which can be calculated from simple digital data extracted from the gauge profiles. The suggested procedure is to extract the relative heights of points at 5 mm horizontal intervals. This can be done very easily using a digitizing tablet which yields x and y coordinates. Roughness indices can now be calculated using a range of measurement intervals so that it is possible to investigate the scale as well as the magnitude of roughness. Where the measurement intervals exceed 5 mm they can be overlapped. The most useful indicator of both the scale and the magnitude of roughness is the standard deviation of the differences between adjacent height values (index A). An array of results obtained using different measurement intervals can be presented as a 'deviogram'. The regression approach (root-mean-square roughness), which uses the standard error of the y-estimate, provides a convenient measure of the magnitude of roughness and is most sensitive to the largest scale of irregularities present.

In the accompanying *Technical and Software Bulletin* a template is supplied which automates the calculation of roughness index A from 19 cm profiles. Values are calculated using measurement intervals of 5 mm, 10 mm, 15 mm, 20 mm, 25 mm and 30 mm and are presented as a 'deviogram'. The 'deviogram' is proposed as the optimum way to quantify and display both the magnitude and scale of roughness of rock surface profiles. The regression approach, or root-mean-square (r.m.s.) roughness, provides a useful single measure of roughness at the largest scale present but will yield anomalously high values where the scale of roughness is small but the surfaces are not planar.

This standard procedure allows the roughness of rock surfaces to be recorded and quantified easily and quickly using inexpensive equipment and simple software. The roughness indices are sensitive to both the scale and magnitude of surface roughness and are easy to interpret. The interval-scale data are appropriate for a wide range of statistical tests. The three brief case studies demonstrate that rock surface roughness provides a useful surrogate measure of degree of rock surface weathering for use in studies of processes and rates of weathering and in relative-age dating.

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